Slovak Journal of Civil Engineering

Vol. 33, 2025, No. 1, 55 – 63
DOI:10.2478/sjce-2025-0006

EXPERT ESTIMATES OF THE POTENTIAL OF AR, VR, BIM AND AI TECHNOLOGIES TO SUPPORT SUSTAINABLE CONSTRUCTION 4.0 IN SLOVAK CONSTRUCTION SECTOR

Martina PORUBČINOVÁ[1*], Ondrej GAJNIAK[2], Richard HERIBAN[1]

Abstract

This paper presents the findings of theoretical and empirical research in the area of sustainable Construction 4.0. In the theoretical part of the article, the findings of the potential of BIM technology to support the development of sustainable Construction 4.0 which are based on a literature review study of the works published in the examined area are presented. In the empirical part of the work, the article discusses findings related to the potential of BIM technology in the specific dimensions of sustainable Construction 4.0 based on expert assessments of a sample of 94 experts in construction sector in Slovakia. The potential of BIM technology was identified for social, economic and environmental dimensions of the development of the development of sustainable Construction 4.0. The significance of the differences among the expert estimates for the different sustainability dimensions and among the expert groups are verified.

Address

[1] The Institute for Forecasting, Centre of Social and Psychological Sciences, Slovak Academy of Sciences, Bratislava, Slovakia

[2] Dept. of the Humane Sciences, Faculty of Civil Engineering, Slovak University of Technology, Bratislava, Slovakia

[*] ***Corresponding author:*** progmpor@savba.sk

Key words

- BIM,
- Construction 4.0,
- Sustainability.

1 INTRODUCTION

Dynamic business environments can be faced with sudden and unforeseeable complexities (Sugeri et al., 2021), a changeable environment, and a fragmented supply chain (Wang and Guo, 2022). The current challenges of energy crisis and the pandemic period have brought challenges for the sustainable development of the construction sector. In Slovakia, we have seen a continuous decline in the digitalization process since 2020 (1); currently, one quarter of companies are digitalizing, compared to 35% of the companies in 2020 (Miškerík, 2023).

Although there are a number of specific challenges to the innovative development process in the CS due to its fragmented and complex nature and difficulties coordinating the number of participants (Olapado, 2006), since 2021, we have been witnessing increased attention to Sustainable Construction 4.0 (SC4) (Franco et al., 2022). Space is opening up for following the potential of Innovation 4.0 to support the sustainability of production processes.

The SC4 framework has been identified and supports efficiency, a lower environmental impact, and social sustainability, including construction costs, and impact analyses of CO2 emissions of the construction industry (Costa et al., 2019). Synergetic effects of various principles integrated with SC4, such as environmental sustainability, lean principles, project management, health, security, and environment management, the development of worker skills, and the Industry 4.0 concept have been presented. Oti et al. (2016) developed a life cycle approach to observe the sustainability of production processes from a more concise perspective. Mesquita et al. (2022) have presented the integration of lean principles, environmental sustainability, and Industry 4.0, based on various linkages that have been confirmed between these three principles.

The potential of Innovations 4.0 to support sustainable development has become one of the research interests within the Construction 4.0 framework. The key research goal of the paper is to bring empirical evidence of the potential of BIM technology to support sustainability in the construction sector. BIM technology was selected for the research purposes of this study, as it belongs among the most examined technologies and leading innovative domains within SC4 research (Statsenko et al., 2022; Kozlovska et al., 2021). BIM technology has been followed as a reliable approach for sustainable construction practices in published research work, especially in the last five years (Santos, 2019).

According to the empirical findings of the implementation of BIM in Slovakia by Funtík et al. (2023), the adoption of BIM has reached 21.1% with more use in buildings (27,8%), compared to 8.8% in the infrastructure. Based on the study, 68.34% of BIM users adopted BIM on their own incentive, while only 8.98% were working under requirements for BIM. The share of professionals not interested in BIM is 46% in Slovakia compared to 1% in the United Kingdom.

To support evidence-based decision making for the acceptance of BIM, this study presents empirical evidence on the quantification of the potential of BIM technology to support the development of SC4 development, based on expert estimates collected in the Slovak construction sector.

2 THEORETICAL PART - METHODS AND RESEARCH PURPOSES

In the first part of the article, a literature review (LR) is conducted in order to provide a theoretical background of the area examined and to precisely select and identify research questions and create specific data collection tools. The benefits of a LR are the provision of an overview of the research findings published this far and an understanding of the broader context of the area monitored (Mareš, 2013). The research question for the LR research is as follows: 1. What is the potential of BIM technology to support the SC4 sector in the dimension of economic sustainability (EcoS), environmental sustainability (EnviS), and social sustainability (SoS), based on the published research findings?

3 RESULTS OF THE LITERATURE REVIEW STUDY ON BIM'S POTENTIAL IN SUSTAINABLE CONSTRUCTION 4.0 - BIM TECHNOLOGY IN SC4

By initially creating an intelligent 3D model, BIM technology enables simulation, document management, coordination, integration, communication, and collaboration between project stakeholders (Darko et al., 2020). Studies of BIM within the framework of SC4 have been presented by various authors (Ekasanti et al., 2021; Eberthäuser et al., 2019; Jalaei et al., 2015; Zuklefli et al., 2020; Panteli et al., 2020; Adanič et al., 2021; Koltsios et al., 2022; Oke and Arowoiya, 2022; Shin and Cha, 2023; Akbarieh et al., 2020; Stock et al., 2018).The integration of BIM and various sustainability-supporting tools have been presented, either by BIM and the integration of sustainability assessment integration tools for more straightforward, faster, and intuitive automatic analysis of construction projects (Santos et al., 2019; Carvalho et al., 2020), or by the integration of BIM and facility and safety management tools for more effective modular construction (Darko et al., 2020; Loo et al., 2023). In the EcoS, BIM can create 10% cost savings and a 7% flat time reduction (Fernández-Mora et al., 2022) via optimizing algorithms, reduced time in unbudgeted changes and the higher accuracy of cost estimates. Based on IT-supported improvements of team, material, marketing, and health and security management, BIM can potentially reduce or eradicate fragmentation in the building delivery process (Fadey, 2017). Based on the application of sustainable rating systems and assessment tools, EnviS highlighted the potential of BIM to enhance the green design of highways (Rooshdi et al., 2021). Utilization of energy use in construction via application of Autodesk Revit and Autodesk Insight BIM has been employed (Zhang et al., 2020).

In SoS, the application of BIM for improving the safety of construction workers was identified as one of the prominent research clusters within current research trends in SC4, with the subthemes of skills, training, perception, hazards, and safety responses based on the scientometric mapping method (Ghosh et al., 2021). As the effectiveness of labour has been identified in relation to the safety and motivation of the workers (Fadey, 2017), the creation of a safe environment and improved construction methodologies can increase the motivations to work on construction sites. In the SoS dimension, BIM can also be viewed as a skill, the knowledge of which is essential for future construction professionals.

3.1 BIM and integration with AI, VR/AR in SC4 - Hybrid innovations

As stated by Xu et al. (2022), hybrid innovations that integrate two or more types of smart technology have the potential to improve health, safety and environment management in the areas of training and safety inspection management systems. The integration of BIM and IoT technology has been applied in structural health and safety management, the transmittions of vibrations and cracks, and the state of building materials and civil constructions, such as historic bridges and monuments (Mohammed et al., 2022). The integration of BIM and VR enables field workers to visualize design models with detailed objects and attributes directly before construction, especially those of complex models (Khalil, 2021). Collaboration and interoperability among partners through the use of integrated visualisation technologies in SC4 is in line with the communication and information sharing basis of the Industry 4.0 innovation concept.

The integration of BIM, IoT, and VR in EnviS was tested to measure real-time thermal comfort conditions. A deeper data environment based on BIM and IoT integration can thus improve energy and environmental performance in buildings, while lowering operating costs and consumption (Mohammed et al., 2022).

Combining BIM with blockchain technology supports information management in the value-chain of sustainable building design and workflow by identifying the circularity potential of building elements (Yevu et al., 2021). Studies have been realized that follow the integration of BIM and BEM (building energy model) to improve the building design process (Bastos Porsani et al., 2021).

BIM has been integrated with geographic information systems (GIS) (Wang et al., 2019; Zhang et al., 2020), although there have been challenges in the integration of BIM and geospatial data (Darko et al., 2020). According to (Zhang et al., 2020a; Pessoa et al., 2021), the integration of BIM and 3D printing has been very effective for saving energy, decreasing costs and benefiting building design. A summary of the key findings of LR is presented in Tab 1.

Tab. 1 *Potential of BIM technology in EcoS, EnviS and SoS in SC4*

Economic Sustainability	Environmental Sustainability	Social Sustainability
Optimization of cost estimations, construction schedules (Zuklefli et al., 2020) Reduced time dealing with unbudgeted changes, higher degree of accuracy of cost estimation via optimizing algorithms (Fernández- Mora et al., 2022) Effective integrated management and project planning (Zhang et al., 2020), reduce operating costs and consumption (Mohammed et al., 2022), save time and permits faster and intuitive automatic analysis of construction projects (Carvalho et al., 2020) Reducing or eradicating fragmentation in the building delivery process (Fadey, 2017). Improving labour effectiveness and motivation of workers through creation of safe environment and improved construction methodologies (Fadey, 2017) In integration with 3D printing; saving energy, decreasing costs and benefiting building designs (Zhang et al., 2020; Pessoa et al., 2021)	Improving energy use and environmental performance (Zhang et al., 2020; Mohammed et al., 2022) Improving green design of highways based on application of sustainable rating systems and assessment tools (Rooshdi et al., 2021) Postconstruction monitoring and energy as sessment of buildings (Fokaides et al., 2020, Panteli et al., 2020) Minimizing construction and demolition waste (Akbarieh et al,. 2020)	Simulation, document management, coordination, integration, communication, and collaboration between project stakeholders (Darko et al., 2020), Encouraging teamwork by information exchange among partners, effective integrated management and project planning (Zhang et al., 2020) Monitoring health and safety issues (Ghosh et al., 2021, Panteli et al., 2020)

4 EMPIRICAL METHODS AND RESEARCH PURPOSES

In the empirical part of the research, we examined the potential of the BIM technology in SC4 through expert assessments of the construction sector in Slovakia via an online questionnaire. The key empirical research question was set as follows: What is the potential of BIM technology to support EcoS, EnviS, and SoS in SC4 based on xpert estimates in the Slovak construction sector?

The hypotheses to be verified were established as:

H1: *There is a significant difference in the potential of BIM technology to support economic, environmental, and social sustainability in SC4, based on expert assessments.*

H2: *Based on expert assessments, there is a significant difference in the potential of BIM technology to support economic, environmental and social sustainability in relation to the profession of the experts and the extent of their experience with BIM technology.*

Various sets of indicators have thus far been presented in papers to empirically verify the Innovations 4.0 potential in SC4. The indicators of the positive and negative effects of Construction Innovations 4.0 were identified for the economic sustainability dimension (EcoS) (e.g., by budget overruns, project delays), social sustainability (SoS) (e.g., by a high accident rate, the safety and well-being of the workers) and environmental sustainability (EnviS) (e.g., in relation to the high consumption of material and energy, construction waste, and noise production, and vehicular traffic near construction sites (Wang-Guo, 2022, Loo-Wong, 2023). Wang and Guo (2022) proposed a set of indicators for the triple-bottom line (TBL) sustainability dimensions, which include wage indicators, working, health and safety conditions, ethics and privacy considerations (SoS), operational and maintenance costs, collaboration, financial feasibility (EcoS) and raw material used, recycled material used, energy consumption, renewable energy utilized, emissions and waste growth (EnviS).

To quantitatively measure the potential of the technology examined in SC4, we selected indicators for the variables “EcoS”, “EnviS” and “SoS”, based on the study of the literature in the SC4.0 papers. The operationalized sustainability dimensions indicators are presented in Tab. 2.

The “work position” variable was operationalized by the type of the expert profession as “academic” (teacher of the Faculty of Civil Engineering of STU) or “business” (architect/designer, budget manager, surveyor, construction manager/foreman, construction technician, building management, construction machinery operator).

Tab. 2 *Indicators of EnviS, EcoS and SoC dimensions of sustainability in SC4*

Environmental sustainability	saving energy, reduction of construction waste and CO2 production, use of ecologica use of low-carbon and recycled materials, water use reduction
Economic sustainability	cost savings, efficiency and productivity of work, reduces time costs of work, better coordination and cooperation in the creation of proposals, prevention of malfunctions and defects
Social sustainability	reducing worker efforts, adapting to customer requirements, creating new jobs, health and safety management, protection of workers during training and at work, supporting the transfer of knowledge from other industries, and the development of new competencies

4.1 Empirical findings on the potential of BIM and VR to support SC4 in the Slovak construction sector

In the next part, we present the findings that were gathered through an online questionnaire regarding the potential of BIM technology in SC4 in EcoS, EnviS and SoS in the Slovak construction sector. The empirical data collection was realised via an online questionnaire on a sample of 94 experts in the Slovak consxwtruction sector in January 2024. The sample file was created based on employees of 42 companies associated with the Slovak Green Building Council (SKGBC), who confirmed their interest in cooperation with the data collection, after being contacted by phone. Subsequently, a link was sent to the employees to fill out an online questionnaire. The research sample consisted of 94 experts from practice and the academic sector who are following the sustainable development of the construction sector; there were 66 experts from the practice and 28 experts from the academic sector.

This paper offers a quantitative verification of the differences in the potential of BIM technology in SC4 based on the expert assessments in EcoS, EnviS and SoS. The results shown in Tab. 3 present the findings of the expert assessments on the potential of BIM technology in SoS, EnviS, and EcoS in SC4. The assessed significance of the expert assessments was tested for every sustainability dimension (H1, Tab. 4) and in relation to the experts' profession (H2, Tab. 5).

According to the findings presented (Tab. 3), not only within EcoS, but also within all the monitored dimensions, the respondents estimated the highest potential of technology for the sub-dimensions of “support better coordination and cooperation in the creation of proposals” (M=6.23), “support cost savings” (M=5.81), “prevent breakdowns and defects” (M=5.80), and “support work efficiency and productivity” (M=5.75). In SocS, the respondents estimated the highest potential of BIM technology for the subdimensions “to support adaptation to customer requirements” (M=5.64) as well as to “support the transfer of knowledge from other industries and the development of new competencies” (M=5.42). In EnviS, the highest estimates of the potential of BIM technology were assessed for the subdimensions “to support the reduction of the production of construction waste” (M=5.19) and “the saving of energy in the construction process and the operational energy of the building” (M=5.15). The lowest value of the potential of BIM technology for EcoS was estimated for “supporting the use of ecological, low-carbon, recycled materials and achieving the minimum embodied carbon in construction” (M=4.33), “supporting saving water in building operations” (M=4.71), and “supporting the reduction of the production and operation of CO_2 emissions”(M=4.77). These items were assessed at the lowest rate even within the overall comparison of the sub-dimensions of environmental, ecological and social sustainability in SC4.

Cronbach's Alpha coefficient of internal consistency was used to verify the respondents' estimates in terms of the reliability of the items of the individual subdimensions. The items identifying the individual dimensions of sustainability were tested in order to find out whether these items appropriately identify the factors observed and are internally consistent. The results of Cronbach's test of reliability and Alpha coherence confirmed that the items in the individual stratified groups of the factors are internally coherent and are suitable for monitoring the individual dimensions with regard to the reliability of the instrument used (EcoS Cronbach's α = 0.960, SocS Cronbach's Alpha =0.909 and EnviS Cronbach's α= 0.944, with the required level of Cronbach's α=0.7). After cleaning the data, we created an index value of the estimates for each dimension of sustainability from the average of the five monitored items in each dimension (summation index). Based on the summation index, the highest level of the potential of BIM was assessed for EcoS (M=5.72), for SoS M=0.508 and for EnviS M= 0.486.

In H1 we assumed that based on the experts' estimates, there is a significant difference in the potential of BIM technology to support economic, environmental and social sustainability in SC4. Based on the t-test, the estimated potential of BIM technology in the EcoS dimension was significantly higher compared to SocS (t=-6.946, $p<0.05$) as well as compared to EnviS (t=-6.755, $p<0.05$). Within EcoS, the distribution of the potential estimates in the individual items (subdimensions) reached a higher level of homogeneity, with a tendency towards more positive values of the potential of BIM (skewness=-0.542) compared to Soc S and EnviS. The results of the t-test did not confirm a statistically significant difference in the estimates achieved of the potential of BIM technology to support between SoS and EnviS (t=-1.911, $p>0.05$).

Based on the verification of the correlations between the individual summation indices (paired sample correlations test), the higher the respondents assume the economic potential of BIM, the higher the potential they perceive and also estimate also for EnviS (0.689, $p<0.05$). Similarly, the higher they estimate the potential of BIM to support EcoS, the more they perceive the technology's potential within SocS (0.782, $p<0.05$) (Tab. 4).

In H2, we assumed that *there is a significant difference in the potential of BIM technology to support economic, environmental and social sustainability in relation to the profession of experts and the extent of the experts' experience with BIM technology.* When comparing the experts' estimates from the business and academic environments, the experts from the academic area estimated the potential of BIM higher in all three dimensions of sustainability compared with the experts from business, but the difference between the experts was not statistically significant in any of the dimensions observed (Tab. 5).

The experts were screened for their level of BIM expertise by answering the question: “*Please indicate whether you have encountered BIM technology in practice; how long you have experience with it, and how long you have been using it.*" Of the total number of respondents, 23.4% do not use and do not plan to use BIM; 40.4% do not use BIM but are considering its potential use in the future; 3.2% have been using it for less than one year;13.8% have been using it for 1–3 years;8.5% for 3–6 years; and 10.6% have been using BIM for more than 6 years. After verifying the correlations between the use of BIM technology and the estimated potential of the technology in terms of sustainability using Spearman's coefficient, significant correlations were confirmed for selected aspects of social sustainability: the longer users have been using BIM technology, the higher the potential they attribute to it in supporting job creation (S = 0.324, App. Sig = 0.006), enhancing coordination and collaboration in design processes (S = 0.218, App. Sig = 0.05), and preventing defects and failures (S = 0.224, App. Sig = 0.05).

Q: Please indicate to what extent you agree with the following statements when using BIM technology (on a scale from 1 - do not agree at all, 7 - completely agree), source: own findings

Tab. 3 *The potential of BIM technology in the environmental, social and economic dimensions of the sustainability of Construction 4.0 according to the estimates of experts of the construction sector in Slovakia*

Environmental sustainability (M=4.86)	**N**	**M (SD)**	
The use of BIM has the potential to support the saving of ENERGY in the construction process and the operational energy of the building production.	73	5.15 (1.630)	8-9
The use of BIM in the construction process has the potential to support the reduction of construction WASTE production.	77	5.19 (1.614)	7
The use of BIM has the potential to support the reduction of CO2 production and the saving of operational CO2 emissions.	71	4.77 (1.758)	11
The use of BIM in the construction process can support the use of ecological, low-carbon, recycled MATERIALS and the achievement of minimal embodied carbon in construction.	72	4.33 (1.964)	15
The use of BIM technology has the potential to promote WATER conservation within building operations.	72	4.71 (1.975)	12
Social sustainability (M=5.08)			
The use of BIM technology supports the reduction of workers' workload.	75	4.97 (1.852)	10
The use of BIM technology supports adaptation to customer requirements.	76	5.64 (1.572)	5
The use of BIM technology supports the creation of new jobs.	71	4.37 (1.846)	14
The use of BIM technology supports the protection of health and safety of workers during training and at work.	71	4.66 (1.919)	13
The use of BIM technology supports the transfer of knowledge from other industries and the development of new competencies.	77	5.42 (1.681)	6
Economic sustainability (M=5.72)			
The use of BIM supports cost savings (e.g., thanks to visualization)	80	5.81 (1.692)	2
The use of BIM increases work efficiency and productivity.	79	5.75 (1.660)	4
The use of BIM has the potential to reduce labour time costs.	80	5.15 (1.883)	4
The use of BIM has the potential to support better coordination and collaboration in design.	79	6.23 (1.349)	1
The use of BIM has the potential to support the prevention of failures and defects.	75	5.80 (1.461)	3

Tab. 4 *Correlations between EnviS, EcoS and SocS (by Paired Samples t-test, α=0.05)*

	N	T test	Correlations	Sig.
EnviS & SocS	57	-1.911	0.629	0.061
SocS & EcoS	61	-6.946	0.782	0.000
EnviS & EcoS	62	-6.755	0.689	0.000

Tab. 5 *Estimates of the assessed BIM potential for EnviS, EcoS, and SocS by the expert groups and the statistical significance of the differences (t-test, α=0.05)*

	Groups	N	M (Std.dev)	T test	Sig
EnviS	business	45	4.64 (1.604)	-1.797	0.77
	academic	20	5.30 (1.15)		
SocS	business	41	4.97 (1.30)	-0.010	0.789
	academic	21	5.29 (1.24)	N	N
EcoS	business	50	5.54 (1.56)	-1.602	0.059
	academic	23	6.10 (0.94)		

5 CONCLUSION

This paper presents the findings of the theoretical and empirical research in the area of the potential of BIM technology to support the development of sustainable Construction 4.0 from a TBL perspective that follows the economic, environmental and social dimensions of sustainability.

A strategy of sustainable development, which has grown from various environmental movements (Rooshdi et al., 2021) has been identified as consistent with the triple-bottom line perspective (TBL), which has struck a balance between environmental, economic and social performance in construction in several previous studies (Wang-Guo, 2022; Franco et al., 2022; Balasubmaranian et al., 2021). As stated by Balasubmaranian (2021), the TBL approach offers a tool for estimating the potential of Innovations 4.0 to support SC4 and follows the achievement of interrelated and sustainable development goals.

In the theoretical part of the work, findings on the potential of AR, VR, BIM and AI technology to support the development of SC4 were presented. Based on the findings of the literature review, the potential of AR, VR, BIM and AI in SC4 was empirically tested by several authors (e.g., Abidi et al., 2022; Arsiwala et al., 2023; Arashpour et al., 2022; Nabeeh et al., 2022; Oke and Arowoiya, 2022). The findings on the potential for AR tools to be applied in construction work, project documentation, planning, monitoring and modifications, on-site real-time information retrieval, and health and safety measures were confirmed without any significant differences among the assessments of the construction experts by the authors (Oke and Arowoiya, 2022). The findings of Huang et al. (2021) confirmed the essential role of BIM and machine learning integration in saving energy, material and land, and improving the indoor/outdoor environment in the context of BIM and green sustainable building design. The study of the literature study led to the identification of a set of indicators for environmental, social and economic dimensions of sustainability.

For the future, further operationalization of the indicators in examined area will be needed to reflect innovative developments in the area as well as with regard to possible overlapping of sustainability dimensions, such as, e.g., in the case of supporting the creation of new work places or supporting better coordination and cooperation in proposals, that extend from the social dimension of sustainability to the economic dimension. The overlap of multiple indicators can be analyzed in more detail. For example, examining the impacts of "raising work efficiency" in relation to potentially reducing working hours or to increased productivity and a higher volume of projects for a worker could provide valuable insights in the area of the social as well as the economic dimension of sustainability.

The findings indicate that the development and promotion of green BIM present a challenge for the future. Although BIM can work with materials that do not have pre-made BIM objects, this requires manual input. Designers frequently need to combine multiple databases when selecting materials, Therefore, better integration of BIM with EPD systems and material databases is expected to simplify the selection of sustainable products. Current BIM libraries contain standard materials; however, they often lack updated databases featuring low-carbon and recycled materials. A central database of all construction products in the EU does not yet exist, but a database is being developed within the CPR Acquis framework. The most comprehensive databases today include the Environmental Product Declarations (EPD) data (ECO Platform, ÖKOBAUDAT) and BIM models (BIMobject, NBS Source). Creating a central database for low-carbon and recycled products, as well as linking BIM models to material life cycle assessments (such as EPDs), could significantly enhance comprehensive environmental impact analyses. For instance, integrating BIM with LCA software (e.g., One Click LCA, Tally) could automatically compare materials based on EPD data and recommend those with the lowest carbon footprint. Additionally, strengthening regulatory requirements and standards in sustainable construction could further encourage developers and designers to incorporate environmental data into BIM models. To prepare for these challenges, it is essential to not only develop better tools but also enhance users' knowledge of ecological materials and their appropriate selection in BIM technology applications.

In the empirical part of the work, the potential of BIM technology was examined in a TBL perspective based on the subjective assessments of the experts for Slovak construction. Findings on BIM's potential were presented via data collection via a questionnaire on a sample of 94 experts from construction sector in Slovakia. Within the economic, environmental, and social dimensions of sustainable Construction 4.0, the respondents estimated the highest potential of BIM in the areas of a) supporting better coordination and cooperation in the creation of proposals, b) supporting cost savings, c) preventing breakdowns and defects, and d) supporting work efficiency and productivity.

The expert assessments were tested for each sustainability dimension and in relation to the experts' professions and the scope of their experience with BIM. The respondents perceived the potential of BIM technology to be significantly higher in the economic dimensions of the sustainable construction sector compared to the environmental and social sustainability dimensions. Significant correlations were confirmed for selected aspects of social sustainability in relation to the scope of the experience with BIM technology; the longer users have been using BIM technology, the higher they estimate the potential of BIM to they attribute support job creation, enhance coordination and collaboration in design processes, and prevent defects and failures. Significant differences in the experts' estimates in relation to profession (academic, business) have not been confirmed. Significant correlations between the experts' assessments for BIM's potential in the economic, environmental, and social dimensions were confirmed, as the higher the experts estimate the potential of BIM in the economic dimension of sustainability, the higher they estimate its potential for the social and environmental sustainability dimensions. The potential of BIM technology is perceived in the mutual correlations of economic, environmental and social sustainability in construction. This finding could be supportive for further acceptance of BIM technology acceptance and use in the construction sector.

Based on the literature review, future research areas should include issues of health, safety, and environment management in SC4, VR/AR training systems, technical issues of AI application or BIM, and geospatial data integration. According to the LR study findings, there is a need for further development in a cooperative AR/VR environment. A research gap was confirmed in the area of assessing the impact of new technologies in SC4 comprehensively, e.g., in the case of increased electronic waste or just about time deliveries in the context of green BIM.

The limitations of this study are related to the sample size and the subjective assessment base of the empirical data. Empirical findings based on a larger sample of experts could provide more detailed insights into statistical differences in the expert assessments, for example, in relation to the job position and type of company. Additionally, conducting in-depth interviews could offer a more detailed and comprehensive understanding of the potential of BIM and other innovative technologies in Sustainable Construction 4.0.

We agree with Shafei et al. (2022) that awareness of both the benefits and challenges of implementing specific Innovations 4.0 among managers and technicians is a crucial prerequisite for a successful innovation process. This awareness enables evidence-based decision-making regarding the adoption of specific Innovations 4.0. As BIM's adoption is a key approach for the digitization of the construction sector (Funtík et al., 2023), we hope that further empirical evidence on the benefits of Innovations 4.0 within the framework of the SDGs will support the long-term development of sustainable Construction 4.0 and provide a more comprehensive understanding of the acceptance and use of BIM technology.

Acknowledgements

The publication was written within the scope and financial support of the research project VEGA No. 2/0013/24 "*Acceptance and use of Innovations 4.0 in relation to cognitive gains and load in the context of sustainable development goals*".

REFERENCES

BALÁŽ, Miroslav; Michaela DANÁČOVÁ and Ján SZOLGAY. *On the use of the Muskingum method for the simulation of flood wave movements.* Online. Slovak Journal of Civil Engineering, vol. 18 (2010), No. 3, pp. 14-20. Available at: https://doi.org/10.2478/v10189-010-0012-6. [viewed 2024-01-14].

ABIDI, M. Mustufa Haider; Muneer Khan MOHAMMED Muneer Khan and Hisham ALKALEFAH. *Predictive Maintenance Planning for Industry 4.0 Using Machine Learning for Sustainable Manufacturing,* Online. Sustainability, vol.14 (2022), No. 6, p. 3387. Available at: https://doi.org/10.3390/su14063387 [viewed 2024-03-10].

ADANIČ, Luka; Guerra de OLIVEIRA and Andrej TIBAUT. *BIM and Mechanical Engineering—A Cross-Disciplinary* Analysis. Online. Sustainability, vol. 13 (2021), No. 8 p. 4108. Available at: https://doi.org/10.3390/su13084108 [viewed 2024-03-10].

ARSIWALA, Arwa; Faris ELGHAISH and Mohammed ZOHER. *Digital twin with machine learning for predictive monitoring of CO2 equivalent from existing buildings.* Online. Energy & Buildings, vol. 284 (2023), p. 112851. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0378778823000816 [viewed 2024-03-10].

BALASUMARANIAN, Srejith; Vinaya SHUKLA; Islam NAZRUL and Shalini MANGHAT. *Construction Industry 4.0 and Sustainability: An enabling Framework.* Online. IEEE Transactions on Engineering Management, vol. (71) (2021) pp. 1-19. Available at: https://doi.org/10.3390/su13084108 [viewed 2024-03-10].

BASTOS PORSANI, Gabriela; Kattalin Del Valle de LERSUNDI; Ana Sánchez-Ostiz GUTIÉREZ and Carlos Fernández BANDERA. *Interoperability between Building Information Modelling (BIM) and Building Energy Model (BEM).* Applied Sciences, vol.11, (2021), No. 5, p. 2167. Available at: https://doi.org/10.3390/app11052167. [viewed 2024-03-10].

DARKO, Amos; Albert P.C. ChAN; Yang YANG and Mershack O. TETTEH. *Building information modeling (BIM)-based modular integrated construction risk management – Critical survey and future needs,* Online. Computers in Industry, vol. 123 (2020), p. 103327. Available at: https://doi.org/10.1016/j.compind.2020.103327. [viewed 2024-03-10].

EKASANTI, Amalia; Ova Candra DEWI and Nandy PUTRA (2021). *Green BIM Potential in Assessing the Sustainable Design Quality of Low-Income Housing:* A Review. Online. In: IOP Conf. Ser. Material Science. Engineering. Online 098(2):022078. Available at: doi:10.1088/1757-899X/1098/2/022078. [viewed 2024-03-10].

FOKAIDES, Paris A.; Rasa APANAVICIENE; Jurgita ČERNECKIENE; Andrius JURELIONIS…and Tadas ŽDANKUS. *Research Challenges and Advancements in the Field of Sustainable Energy Technologies in the Built Environment,* Online. Sustainability, vol. 12 (2020), No. 20, p. 8417. Available at: doi:10.3390/su12208417. [viewed 2024-03-10].

FRANCO, Jacqueline de Almeida Barbosa; Ana Mariele DOMINGUES; Nelson de Almeida AFRICANO; Rafael Mattos DEUS and Rosane Aparecida Gomes BATISTELLE. *Sustainability in the Civil Construction Sector Supported by Industry 4.0 Technologies: Challenges and Opportunities,* Online. Infrastructures, vol. 7 (2022), No. 3, p. 43; doi:10.3390/infrastructures7030043. [viewed 2024-03-10].

FUNTÍK, Tomáš; MAKYŠ, Peter; ĎUBEK, M; ERDÉLYI, Ján; HONTI, Richard; CEROVŠEK, Tomo. *The Status of BIM adoption in Slovakia.* Online. Buildings, vol 13 (2023), p. 2997. Available at: https://doi.org/10.3390/buildings13122997. [viewed 2024-03-10].

GHOSH, Arka; Jemal ABAWAIY and Morshed CHOWDHURY. *Redefining the construction managerial landscape to facilitate Industry 4.0 implementation: scientometric mapping of research frontiers,* Online. Construction Innovation, vol. 24 (2022), No.4, p.27. Available at: 10.1108/CI-11-2021-0224. [viewed 2024-04-10].

JALAEI, Farzad; Farnaz JALAEI and Mohammadi Sepher. *An integrated BIM-LEED application to automate sustainable design assessment framework at the conceptual stage of building projects*,Online. Sustainable Cities and Society, vol. 53 (2020) p. 101979. Available at: https://doi.org/10.1016/j.scs.2019.101979. viewed 2024-04-10].

KHALIL, Ayah-Allah; Mohamed FIKRY and Waled ABDEAAL. *High technology or low technology for buildings envelopes in residential buildings in Egypt.* Online. Alexandria Engineering Journal, vol. 57 (2018), No. 4, pp. 3779–3792. Available at: https://doi.org/10.1016/j.aej.2018.11.001 [viewed 2024-04-10].

KOLTSIOS, Stavros; Paris FOKAIDES; GEORGALI, P.Z....and TZOVARAS, D. *An enhanced framework for next-generation operational buildings energy performance certificates.* Online. International Journal of Energy Research, Special Issue (2022). Available at:doi:10.1002/er.8517. [viewed 2024-04-10].

LOO, Becky P.Y and Rosana W.M. WONG. *Towards a Conceptual Framework of Using Technology to Support Smart Construction: The Case of Modular Integrated Construction (MiC).* Online. Buildings, vol. 13 (2023), No. 2, p. 372. Available at: https:// doi.org/10.3390/buildings13020372. [viewed 2024-03-10].

MESQUITA, Lígia Lobo; Fabiane Letícia LIZARELLI; Susana DUARTE and Pedro Carlos OPRIME. *Exploring relationships for integrating lean, environmental sustainability and industry 4.0,* Online. International Journal of Lean Six Sigma, vol. 13 (2022), No. 4, pp. 863-896. Available at: 10.1108/IJLSS-09-2020-0145. [viewed 2024-03-10].

MIŠKERÍK, Martin. *Firmy chcú digitalizovať, len nevedia ako. Companies want to digitalize, they just don't know how,* Trend No. 12, 23.3. 2023. Available at: https://www.trend.sk/trend-archiv/firmy-digitalizovat-chcu-len-nevedia-ako-chybaju-im-digitalni-manazeri-lepsie-znalosti. [viewed 2024-03-10].

MOHAMMED, Baydaa Hashim; Hasimi SALLEHUDIN, Shaymaa ABDELGHANY Mahamed, Nurhizam Safie Mohd SATAR, Afifuddin Husairi bin HUSSAIN. *Internet of Things-Building Information Modeling Integration: Attacks, Challenges, and Countermeasures,* IEEE ACCESS, vol.10 (2022), pp. 74508-74522. Available at:: 10.1109/ACCESS.2022.3190357. [viewed 2024-03-10].

NABEEH, Nada A.; Mohamed ABDEL-BASSET; Abdullah GAMAL and Viktor CHANG. *Evaluation of Production of Digital Twins Based on Blockchain Technology.* Online. Electronics, vol. 11, (2022), No.8, p. 1268. Available at: doi:10.3390/electronics11081268. [viewed 2024-03-10].

OKE, Ayodeji E. and Victor Adetunji AROWOIYA. *Ananalysis of the application areas of augmented reality technology in the construction industry,* Online. Smart and Sustainable Built Environment, vol. 11 (2022), No. 4, pp. 1081-1098. Available at: DOI 10.1108/SASBE-11-2020-0162. [viewed 2024-03-10].

PANTELI, Chrisitana; Angeliki KYLILI and Paris A. FOKAIDES. *Building information modelling applications in smart buildings:* From design to commissioning and beyond; A critical review,Online. Journal of Cleaner Production, vol. 265 (2020), No. 1, p. 121766. Available at: 10.1016/j.jclepro.2020.121766. [viewed 2024-03-10].

PORSANI, Gabriel Bastos; Kattalin; Del Valle de LERSUNDI; Ana Sánchez-Ostiz GUTIÉRREZ and Carlos Fernández BANDERA, *Interoperability between Building Information Modelling (BIM) and Building Energy Model (BEM),* Online. Applied Sciences, vol.11 (2021), No. 5, p. 2167. Available at: https://doi.org/10.3390/app11052167. [viewed 2024-03-10].

Half-year study of the Slovak construction industry H1/2021, CEEC Research, available at: https://www.archinfo.sk/diskusia/blog/vykon-povolania/polrocna-studia-slovenskeho-stavebnictva-h1-2021-ceec-research.html.

ROOSHDI, Raja Ratifah Muhammad; Noor Akmal Adillah ISMAIL; Shaza Rina SAHAMIR and Mohd Arif MARHANI. *Integrative Assessment Framework of Building Information Modelling (BIM) and Sustainable Design for Green Highway Construction:* A Review, Online. Chemical Engineering Transactions, vol. 89, (2021), pp. 55-60. Available at: DOI:10.3303/CET2189010. [viewed 2024-06-10].

SHAFEI, Hazwani; Afiqah R. RADZI; Mohammed ALGATHANY and Rahimi A. RAHMAN. *Construction 4.0 Technologies and Decision-Making: A Systematic Review and Gap Analysis,* Online. Buildings, vol. 12 (2022), No. 12, p. 2206. Available at: https://doi.org/10.3390/buildings12122206. [viewed 2024-06-10].

SHIN, Hyeon-Ju and Hee-Sung CHA. *Proposing a Quality Inspection Process Model Using Advanced Technologies for the Transition to Smart Building Construction,* Online. Sustainability, vol.15 (2023), No. 1, p. 815. Available at: doi:10.3390/su15010815. [viewed 2024-06-10].

STOCK, Tim ; Michael OBENAUS; Sascha KUNZ and Holger KOHL. *Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential.* Online. Process Safety and Environmental Protection, vol. 118 (2018) pp. 254-267, Available at: https://doi.org/10.1016/j.psep.2018.06.026. [viewed 2024-06-10].

VITE, Clara and Renata MORBIDUCCI. *Optimizing the Sustainable Aspects of the Design Process through Building Information Modeling,* Online. Sustainability vol. 12 (2021), No. 6, p. 3041. Available at: https://doi.org/10.3390/su13063041. [viewed 2024-06-10].

WANG, Kaiyang and GUO, Fangyu. *Towards Sustainable Development through the Perspective of Construction 4.0: Systematic Literature Review and Bibliometric Analysis,* Online. Buildings, vol. 12 (2022), No. 10, p.1708. Available at: doi:10.3390/buildings12101708. [viewed 2024-06-10].

XU, Maozeng; Nie XIUYING; Li HENG; Jack C.P. CHENG and Zhongya MEI. *Smart construction sites: A promising approach to improving on-site HSE management performance,* Online. Journal of Building Engineering, vol. 49 (2022), p. 104007. Available: https://doi.org/10.1016/j.jobe.2022.104007. [viewed 2024-06-10].

YEVU, Sitsofe Kwame; Ann T.W. YU and Amos DARKO. *Digitalization of construction supply chain and procurement in the built environment: Emerging technologies and opportunities for sustainable processes.* Online. Journal of Cleaner Production, vol. 322 (2021), No. 6, p. 129093. Available at: doi: 0.1016/j.jclepro.2021.129093. [viewed 2024-06-10].

ZHANG, Jie; Xuping ZHU; Abdul Mateen KHAN; Moustafa HOUDA; Sardar Kashif Ur REHMAN; Mohammed JAMEEL; Muhammad Faisal JAVED and Raid ALROWAIS. *BIM-based architectural analysis and optimization for construction 4.0 concept (a comparison),* Ain Shams Engineering Journal, vol. 14 (2023), No. 6, p. 102110. Available at: https://doi.org/10.1016/j.asej.2022.102110. [viewed 2024-06-10].

ZULKEFLI, Nur Syamini; Fayzul Azri MOHD-RAHIM and Nurshuhada ZAINON. *Integrating Building Information Modelling (BIM) and Sustainability to Greening Existing Building: Potentials in Malaysian Construction Industry. International Journal of Sustainable Construction Engineering and technology,* vol.11 (2020), No. 3, pp.76-83. Available at: doi:10.30880/ijscet.2020.11.03.008. [viewed 2024-06-10].